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Three Dimensional Acoustical Imaging Based on Isosurface Technique for Bulk Material

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Abstract: The paper introduces the methods with time-resolved technique and isosurface display technique to get two- and three-dimensional (3D) acoustical imaging for scanning acoustic microscopy. Time-resolved technique presents the way to realize two-dimensional (2D) acoustical imaging – A- (O-), B- and C-scan, and a discrete combinatorial 3D image; and isosurface display technique realizes a 3D image with continuous distribution in full direction. The paper proposals a transitional model of square column, which consists of the data of echo signal pattern extracted from volume database, to construct the imaging cube and depict an isosurface using isovalue of internal boundaries in the cube, for the evaluation of internal defects in bulk specimen – Boron Nitride. 3D acoustical imaging has the advantage to show the position, size, appearance, distribution, and tendency of internal structures (voids, inclusions and defects) with complex shapes in non-transparent bulk material. The results show that 3D acoustical visualization presents more affluent, overall and intuitive pattern than 2D imaging for micro-sized structure investigation. *Copyright © 2013 IFSA.*

Keywords: Scanning Acoustic Microscope, Echo Signal Pattern, A-scan, B-scan, C-scan, Three Dimensional Acoustical Imaging, Isosurface Technique, Internal Defects, NDT/E, Boron Nitride.

1. Introduction

The technologies of Scanning Acoustic Microscopy (SAM) and their applications are based on the raster principle, which was proposed by C. F. Quate and R. A. Lemons in 1974. High-frequency ultrasound usually more than 20 MHz is employed to produce a focused probe beam in immersion, with a focal spot diameter in tens of micrometers [1-3]. This ultrasound probe beam penetrates into the bulk material, and its response radiation makes it possible to imaging micro-sized structure of a bulk specimen with micron or submicron resolution.

Ultrasound wave is very sensitive to the varieties in focal spot. Response radiation coming from the focal region of the probe beam output as an ultrasound signal, which is formed by the interaction between the ultrasound probe beam and the internal structure elements inside local insonificated region. It can be employed to investigate some physics elastic properties – calculating acoustic wave velocities (longitudinal wave and transversal wave) by the time interval between various ultrasound signals, and investigating acoustical phenomena by analyzing signal formation in echo signal pattern [4, 5]. Another utility of response radiation is a means to form acoustical imaging. Acoustical imaging possesses its own mechanisms of acoustical contrast – specific ways to represent structural peculiarities of objects. Variations of signal parameters coming from diverse points of bulk material are displayed in the screen as a pixel of acoustical image.

At present, acoustic microscopy provides the mature two-dimensional (2D) imaging techniques, including A-(O-), B- and C-scan image, to evaluate the micro-sized structures in non-transparent solid bulk material.

In many modern high-tech industrial fields, the micro-sized internal defects inside the solid bulk material hide extreme risk in some applications. The material of Boron Nitride (BN) is a very modern and popular bulk material [6, 7]. It has wide range of application in the fields of aerospace and aviation industry, semiconductor and metal processing. Boron Nitride is used in wear-resistant and erosion-resistant coatings and thermal barriers in thermal spray coatings on the turbine engines, as dynamic friction materials in brake pads, as well as thermal management fillers in high-performance plastic components. Its elastic properties determine it is a fragile material, once in which there is any internal defects, the defects spread to the whole bulk and lead to full fracture. Hence, the microscopical inspection of internal defects for Boron Nitride material is prerequisite for some vital applications.

Scanning acoustic microscopy just provide the technology to detect the internal defects for this purpose in a non-destructed testing/evaluation (NDT/E) way [3, 8]. However, the traditional 2D acoustical imaging only presents internal structure information discontinuously, individually, and lack of affluent, intuitive and overall view. In the application of NDT/E field, the three dimensional (3D) acoustical imaging become more attractive for visualization of micro-sized structure. There are two techniques to realize 3D visualization – volume rendering and isosurface rendering [9-11]. Volume rendering sums the weighted contributions of all voxels along the line extended from the viewer's eye through the data volume. It is only used for visualization, and cannot obtain the 3D model of the structures. Isosurface rendering is a high-resolution 3D interface construction technique proposed by W. E. Lorensen and H. E. Cline in 1987. It displays an interface representing the locus of a collection of points in the volume corresponding to a given constant – isovalue. The authors propose a model – 'square column' to match isosurface rendering technique specifically for 3D imaging of scanning acoustic microscopy. Along with the progress of graphic process unit (GPU) technology, the speed of 3D visualization is promoted effectively [12]. Under this background, based on the model of square column and isosurface techniques, and cooperating with the traditional 2D imaging techniques, the 3D acoustical imaging of scanning acoustic microcopy becomes more operable and powerful means, to investigate the micro-sized structure inside bulk materials.

2. Experimental

The specimen is an anisotropic material – Boron Nitride (hexagonal BN), with the sonic velocity of longitudinal wave along x or y plane is about 18.05 mm/μs and along z direction is about 3.44 mm/μs [8]. This specimen is treated into the cuboids' shape – the size with the length is 5.53 mm, the width is 4.8 mm, and the thickness is 4.08 mm. The specimen is put in immersion (water) and implemented by acoustic lens.

Acoustic lens is the kernel of acoustic microscope, carried by a mechanical motion system to realize the scanning and focusing function over the specimen surface. It excites a focused probe beam in immersion and collects the response radiation caused from the micro-sized structure at various depths of the bulk object. The transducer of the acoustic lens receives the reflected ultrasound radiation with the style of mechanical oscillation, and converts it into electrical ultrasound signals, which carry the micro-sized structure information. So, a series of electrical ultrasound signals emerge in an ultrasonic echo signal pattern, named A-(O)-Scan. See the picture a) of Fig. 1.

The picture a) is an experimental pattern, which displays the signals obtained at one scanning point, as the focused probe beam is driven by the mechanical scanning system over the specimen. The ultrasound signals with various amplitudes are distributed along the temporal axis of echo signal pattern, which are corresponded to various structures in vertical direction at a local region on/inside the object. Intensive signal stands for the existence of a boundary (interface) of an internal structure inside the bulk object, and arbitrary background signal means the uniform material inside this bulk object. In the Fig. 1, the symbol A represents that the signal is reflected from the front surface of an object, the symbol B reveals a boundary of internal defect inside this object, and the symbol C reveals the background noise caused by the uniform material.

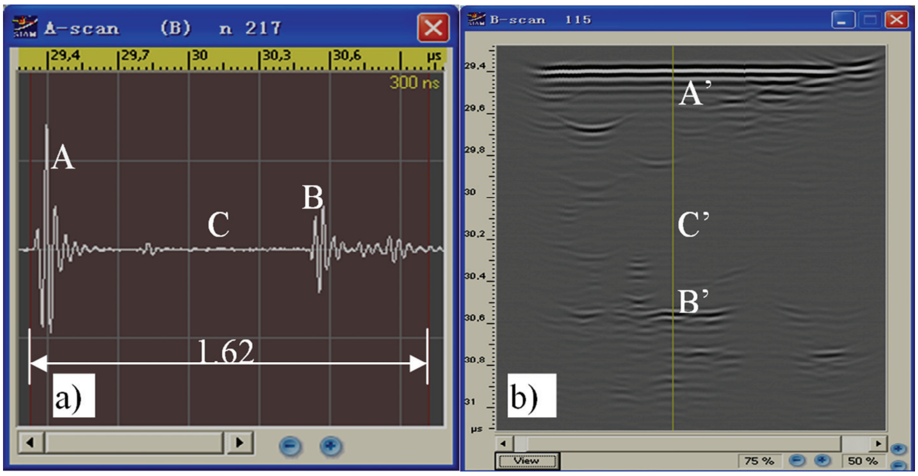

Fig. 1. Echo signal pattern and its scanning result B-Scan image along x direction.

Echo signal pattern is a fundamental data resource for imaging. Under the time-resolved technique, by setting the width of electrical gate in echo pattern, as the focused probe beam is driven along *x* or *y* direction by the mechanical scanning system, the microscopy system acquires the 2D cross-section image – B-scan image. The picture b) of Fig. 1 shows a B-Scan image as the lens is driven along x direction, and the width electrical gate is set to 1.62 µs, in which the pixels marked by symbol A', B' and C' are the scanning results corresponding to the signal A, B and C in the picture a) individually.

In echo pattern, the velocity value in *z* direction of this BN can be derived from the thickness of the specimen, and the time interval between the front surface and bottom. The longitudinal velocity value is 3.03 mm/µs. Meanwhile, the time interval between signal A and B in the picture a) is 1.14 µs, therefore, the depth of the defect inside the specimen can be deduced in 3.45 mm.

As the electrical gate width is set to 340 *ns* in echo signal pattern, and the acoustic lens is driven along x and y direction coordinately, Fig. 2 displays a 2D image – C-scan image, the profile of an internal structure at the depth is 3.45 mm inside this bulk specimen. The bright area with label B'' in different contrast shows this internal interface and its distribution along x or y plane.

Based on 2D acoustical image display techniques, logically, a group of slices consist of 2D images may form a discrete 3D image arranged in parallel as Fig. 3. It presents the simulation of this 3D image with a series of B-Scan images. Every slice is a B-Scan image produced along *x* direction and *z* direction, and the slices are arranged along *y* direction. The set of these pictures provides an approach to characterize the tendency and distribution of internal microstructures. But, between any two adjacent slices, it lost the characterization of some structures.

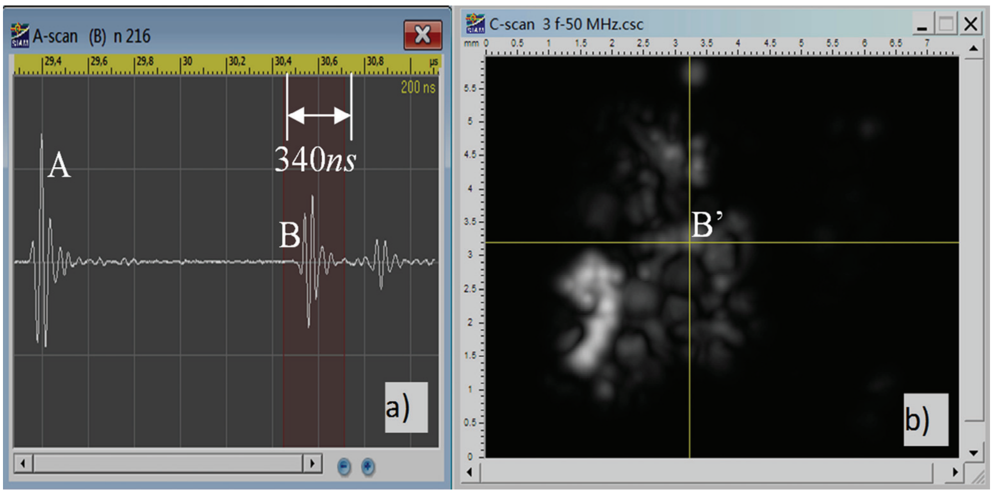

Fig. 2. Selected electrical gate in echo signal pattern and its C-Scan image along x and y plane.

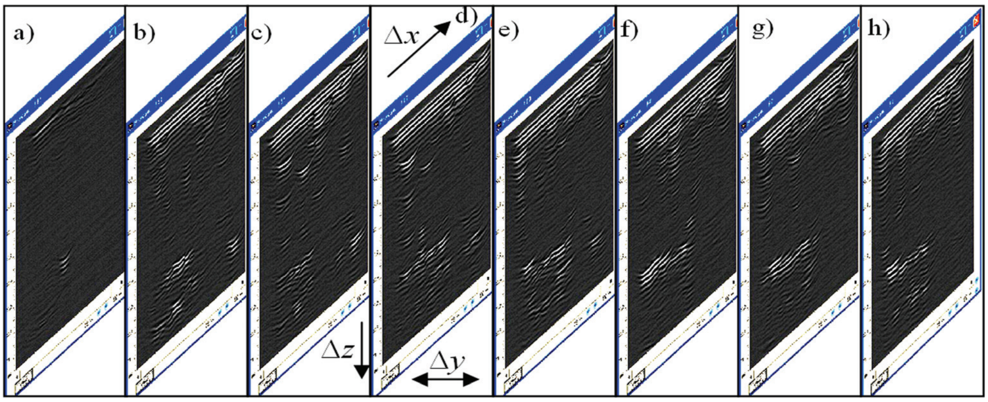

Fig. 3. Internal structures distribution shown in a series of B-Scan images (3D).

Furthermore, our concern is how to construct 3D image employing echo patterns for the real internal structure display in full direction, instead of the display mode with discrete 3D images. The authors build a model of imaging processing unit – square column to realize the 3D visualization, specifically for acoustical imaging.

Within mechanical scanning region, as the acoustic lens moved along x or y direction, the focused probe beam excites the specimen along a series of excitation points – point A, B, C and D … over the specimen front surface. See the Fig. 4. The scanning points create a series of parallel tracks over the surface of specimen. The minimal scanning region is limited within a square grid with the four incident points on the surface of the object. The focused probe beam excites the incident point on the front surface. The spatial distances between these four incident points are Δx or Δy , which are determined by the mechanical scanning precision in two directions. The projections of the incident points A, B, C and D form a square column with four vertical edges - $E_{i,j}$, $E_{i+1,j}$ $E_{i,j+1}$ and $E_{i+1,j+1}$ hidden in the bulk specimen. The vertical edge is wave propagation trajectories, along which the focused probe beam penetrates through and goes back in this minimal local region. Digitalization of echo signal pattern satisfies the demand, to build a square column as a manipulation data unit, which is for constructing 3D image of the real internal structures in full direction using isosurface technique.

3. Methods and Results

Standard isosurface display technique visualizes any structures with various complex shapes, by a way to march through each cube (grid) in turn from the volume data, and to generate a triangulated approximation of the isosurface in each cube [9]. For isosurface display technique, a collection of P is defined to describe the spatial point in volume database, as shown in equation (1):

$$P = (x_i, y_j, z_k), i = 0,1,\cdots,m-1; j = 0,1,\cdots, n-1; k = 0,1,\cdots,s-1 \quad (1)$$

The pair of symbol x, y and z is the spatial position located at coordinate (i, j, k) , the scale value of this position is used for 3D display in the bulk.

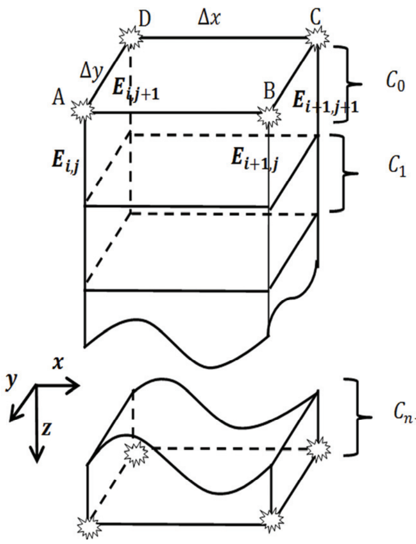

Fig.4. The scanning tracks along A-B and D-C in a minimal scanning region, and the model of a square column.

The model of square column is such a transitional framework, which meets the demand of isosurface display technique specifically for acoustical imaging. According to the physical structure of square column in Fig.4 – a minimal scanning region of SAM, The authors defined this square column in equation (2):

$$C_k = (x_i, y_j, t_k), i = 0,1,\cdots,m-1; j = 0,1,\cdots, n-1; k = 0,1,\cdots,s-1 \quad (2)$$

As the scanning position located at coordinate (i, j) over the object, symbol t is the temporal axis of echo signal pattern; variant *k* is the sampling serial number in echo signal pattern of the square column. The label C_k refers an imaging cube in a square column with the section serial number *k*. Based on the model of square column and the needs of isosurface rendering technique, there are three steps to realize 3D imaging for the application of scanning acoustic microscopy.

3.1. Build all Square Columns from Volume Database

The first is to build all square columns from vast digital volume database. As the acoustic lens marched over the object, the variant of signal amplitude change along with the independent variant *t* of the echo signal pattern. The digital data of echo signal pattern is saved for the bulk information as a basic set, involving all ultrasound signals reflected from all boundaries (interfaces) of the bulk material. See the picture a) – d) of Fig. 5.

The parallel scanning traces of acoustic lens form a series of slices. Logically it produces a series of square columns, coincided with the framework of the model in Fig. 4. Two adjacent scanning points (point A and B) along one scanning track are neighbor with another two points (point D and C) in an adjacent track. These four scanning points form a local scanning region with a pair of coordinates x and y for imaging position. According to four excitation point – A, B, C and D, search four adjacent sets of echo signal pattern from the bulk database synchronously, and build all individual square columns along the scanning track of the lens. The picture e) of Fig. 5 is one section of this square column. Physically, the echo signal pattern with the symbol A-A', B-B', C-C' and D-D' in the picture a) – d) corresponds to four edges of a cube in the picture e) of Fig. 5 individually.

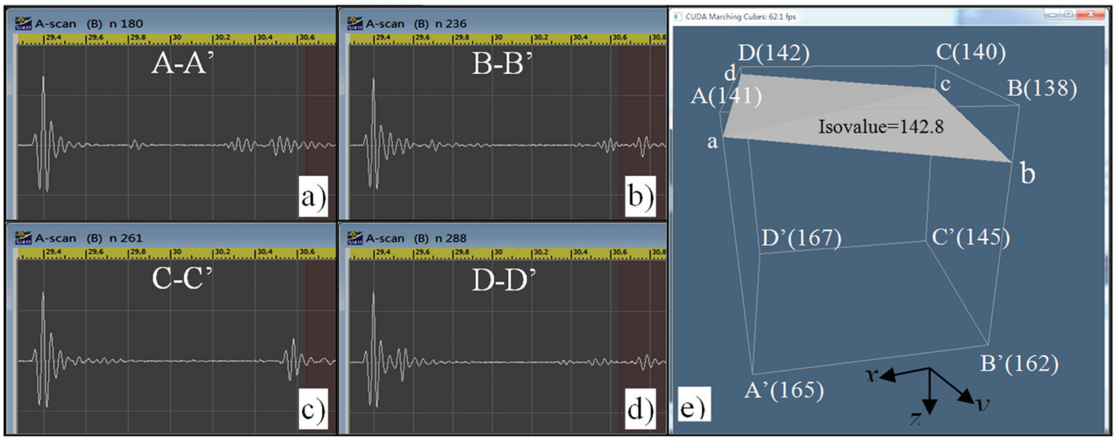

Fig. 5. Synchronistical digital signal in four sets of echo signal pattern of a square column and an imaging cube – P (140, 10, 50), and a local boundary inside the cube.

3.2. Build all Cubes in Every Square Column

The temporal axis of echo signal pattern coincide with the *z* direction of the square column, provides the potential to mapping reconstruction along *z* direction of the bulk. Extract synchronistical digital data from four sets of echo signal patterns to build an imaging cube. The picture a) – d) of Fig. 5 is extracted individually from the bulk database, according to four excitation positions – point A, B, C and D in Fig. 4.

The framework of square column and the equation (2) gives the infer to divide the square column into a series of cubes, in which choosing four neighbor points from one slice and another four neighbor points from the next adjacent slice. The group of eight points is convenient logical block to divide the square column, according to the variant *t* of temporal axis of echo signal pattern. The spatial position is located at coordinate (i, j) over the object, and the label C_k is an imaging cube in a square column with the section serial number *k*. According to the equation (2), a series of cubes are blocked out with the front plane obtained at time t_k, and basal plane at time t_{k+1}.

The picture e) in Fig. 5 gives an experimental example – an imaging cube extracted from a square column, whose position is located at $P(140,10)$. The pair coordinates of eight vertices points of the cube – couple of point A, B, C and D is located individually at the position $P(140,10)$, $P(141,10)$, $P(141,11)$ and $P(140,11)$. The distance between these four vertices is variant Δx or Δy, which is the scanning step along *x* and *y* direction determined by the scanning precision of mechanical system. Its spatial position is 140 steps in x direction and 10 steps in *y* direction. The vertical position in z direction is determined by the sequence of sampling time. The cube in Fig.5 is located between t_{50} (100 ns , 50th sampling point) and t_{51} (102 ns , 51th sampling point) in the square column (the sampling frequency of ADC is 500 MHz).

3.3. Boundary Reconstruction in Every Cube by Isosurface

Each scanning spatial position P has its own scalar value, determined by the signals intensity from the acoustical interaction between internal boundaries and the focused probe beam. The scalar value of the cube vertices in the picture e) of Fig. 5, are used for presetting an isovalue to calculate the isosurface inside this cube. Full direction reconstruction in this local region is obtained by rendering the triangles inside this cube with a constant – isovalue. The surface-edge intersections are calculated, which are used as the triangle vertices in the cube, via linear interpolation at each edge by comparing the eight intensity value of the cube vertices with this isovalue. The isosurface is built as some triangles in the cube, which is an approximate micro appearance (surface) of the boundary in this local spatial region.

The picture e) shows the isosurface (a boundary) in this cube as the isovalue is 142.80. The isosurface – triangle vertex in this cube is constructed with the four vertices – a, b, c and d. The same procedure is repeated to construct boundaries in every cube continuously and individually, by replacing the value t_k with t_{k+1} along the square column, and by moving the sequence of point A, B, C and D to an adjacent square column.

By extension, the system can get all internal boundary spatial distribution in each square column by constructing each cube. This square column only corresponds to one scanning point with the position x and y – a local region of bulk object.

Point by point and track by track in turn as scanning system marching, all adjacent square column units are constructed along the scanning direction. As the result, all internal structures and the spatial distributions in full direction are obtained and displayed in the 3D image – the picture c) in Fig. 6. There are many individual structures (defects, inclusions or voids) with various appearances, distributed below the surface of bulk specimen.

Some structures expand along some directions, presenting a belted distribution inside the bulk marked by a pointed arrow. The picture also presents various complex appearances of structure at subsurface. The 3D results provide an overall and intuitive view than the discrete 3D visualization with a series of B-Scan image slices as Fig. 3.

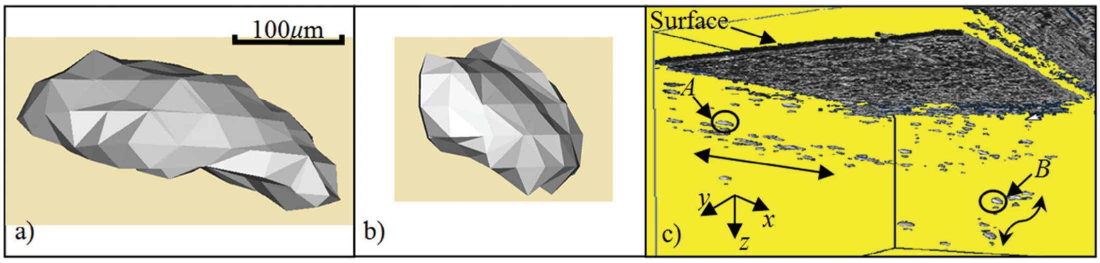

Fig. 6. a) 3D construction result of an internal structure marked by symbol A; b) 3D construction result of an internal structure B; c) 3D overall review of a BN bulk specimen in full direction.

The picture a) and b) of Fig. 6, which are a magnified micro-sized structure with a ragged margin boundary embedded in bulk specimen. This local internal microstructures marked by the symbol A in bulk specimen is completely reconstructed with 4,500 pieces of cubes ($\Delta i = 15$, $\Delta j = 20$ and $\Delta k = 15$) in full direction, with length is 0.308 mm, width is 0.231 mm, height is 0.091 mm, and its depth is 0.171 mm in the bulk. The structure in the picture b) marked by the symbol B is constructed by 1,125 cubes ($\Delta i = 15$, $\Delta j = 5$ and $\Delta k = 15$), with length is 0.077 mm, width is 0.231 mm, height is 0.091 mm, and its depth is 0.303 mm in the bulk.

Reflected intensive ultrasound signals produce a strong contrast for boundary imaging; and the arbitrary signals are ignored to take part in the imaging process through isosurface display technique, presenting a transparent display in the cube.

4. Discussion

For the application of SAM, the difference and the relation between spatial and temporal domain should be taken into account. All data of echo signal pattern used for time-resolved technique, is based on the variation response distributed along the temporal axis. The variant t of temporal axis of echo signal pattern is the indication to divide the square column into a series of cubes for 3D reconstruction.

Thus, based on the concept of isosurface technique and square column, for the spatial distribution specifically for SAM, an improved collection P is proposed as the equation (3) to instead of the equation (1) and (2):

$$P=(x_i, y_j, C_k), i=0,1,\cdots,m-1; j=0,1,\cdots, n-1; k=0,1,\cdots,s-1 \qquad (3)$$

In the equation (3) and the structure in Fig. 4, the pair of x and y is the scanning direction, coordinate (i, j) is the scanning position over the object, the label C_k refers an imaging block (cube) in a square column with the section serial number k. The variant t is a unique reference to divide the square column into a series of basic imaging unit – cube. Digital ultrasound signals of the echo signal pattern just satisfy the condition to block out these imaging cubes from the square column, by counting the sampling time interval of data converter. At each scanning position, the spatial point along the paraxial beam has its own scalar value with various signals intensity reflected from internal microstructures. Therefore, the spatial variant z is indirectly transformed from the temporal variant t of echo signal pattern.

Technically, all digital data of square column (echo signal pattern) are obtained discretely at the node of sampling time. There is no any signal converted in the blind of sampling interval of system. However, the natural spatial distributions of internal structures are expanded continuously in the bulk, with an irregular shape included in a micro-sized cube in full direction, not only limited on eight vertices of the cube. Hence, it is necessary to infill the continuous distributions of internal structures into all space of the cube, by employing isosurface display technique. It is significant to reconstruct the boundary of a structure among the space of this micro-sized imaging cube, to infill the continuous elements of the structure or its continuous varieties in the midst of eight vertices of the cube. Meanwhile, it is possible to simulate it by trilinear interpolation using eight known vertices data of the cube.

5. Conclusion

Digitalization of ultrasound signal provides the chance to save echo signal patterns into a database for huge data storage of a 3D visualization. The authors propose a model – square column, which is used to organize volume data for 3D acoustical imaging. The square column consists of four sets of digital echo signal pattern, and is used to construct a series of imaging cubes. The cube is a basic processing unit and derived from the square column by the sampling time interval of system. Based on it and isosurface technique, the local micro boundary is depicted to fill the space of the cube with the triangles, obtained by calculating the isovalue from the signal intensity of eight vertices in the cube. All elements appearance and distributions in full direction are depicted by the construction of all cubes in all square columns. Intensive signal reflected from the boundary of internal structure in the bulk takes part in the triangle construction in the bulk. The uniform material in the bulk provides a transparent display in bulk imaging, for an arbitrary signal – background noise is absent to the boundary construction. These two facts let the real internal microstructures behind (through) non-transparent material can be displayed in 3D image. The experiment result shows that 3D acoustic image provides an overall view, continuous spectacle to investigate internal microstructures for bulk material than 2D imaging. It provides the information of the position, sizes and the appearance of internal structures (voids, inclusions and defects) with complex shapes, and the distribution and tendency of these internal structures in bulk specimen. Based on the model of square column and isosurface display techniques, 3D acoustical imaging is a practical visualization tool for scanning acoustic microscopy to investigate small scale, non-transparent bulk specimen in NDT/E field.

Acknowledgements

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